# Modes of Operation

# Topics

- **Overview of Modes of Operation**
- EBC, CBC, CFB, OFB, CTR
- Notes and Remarks on each modes

# Modes of Operation

- Block ciphers encrypt fixed size blocks
  - eg. DES encrypts 64-bit blocks, with 56-bit key
- Need way to use in practise, given usually have arbitrary amount of information to encrypt
  - Partition message into separate block for ciphering
- 
- A **mode of operation** describes the process of encrypting each of these blocks **under a single key**
- Some modes may use randomized addition input value

# Quick History

1981
- Early modes of operation: **ECB, CBC, CFB, OFB**
  - DES Modes of operation

    *http://www.itl.nist.gov/fipspubs/fip81.htm*

2001
- Revised and including **CTR** mode and AES
  - Recommendation for Block Cipher Modes of Operation

    *http://csrc.nist.gov/publications/nistpubs/800-38a/sp800-38a.pdf*

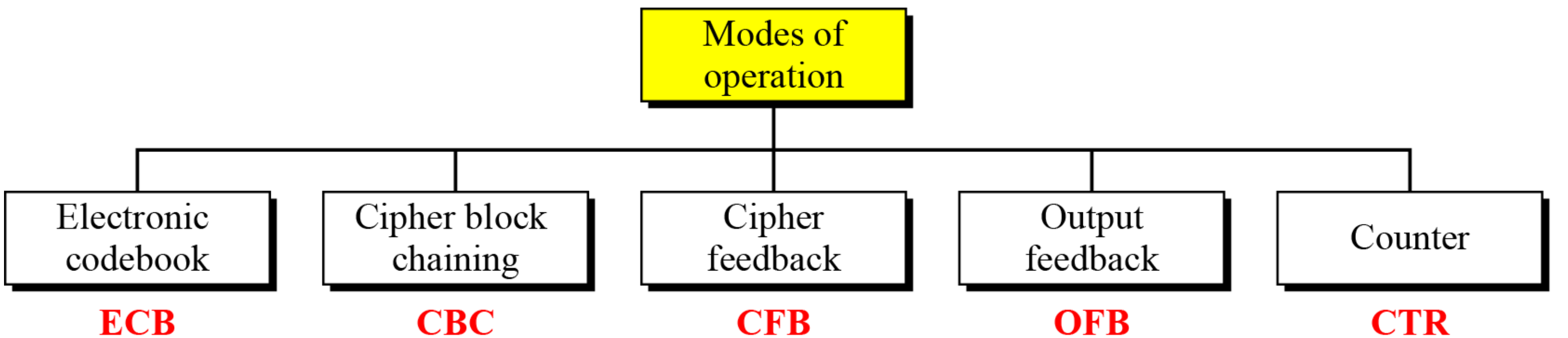
2010
- New Mode : **XTS-AES**
  - Recommendation for Block Cipher Modes of Operation: The XTS-AES Mode for Confidentiality on Storage Devices

    *http://csrc.nist.gov/publications/nistpubs/800-38E/nist-sp-800-38E.pdf*

*Modes of operation are nowadays defined by a number of national and internationally recognized standards bodies such as ISO, IEEE, ANSI and IETF. The most influential source is the US NIST*

# Modes of Operation Taxonomy

- Current well-known modes of operation



# Moe Technical Notes

- Initialize Vector (IV)
  - a block of bits to randomize the encryption and hence to produce distinct ciphertext
- Nonce : Number (used) Once
  - Random of psuedorandom number to ensure that past communications can not be reused in replay attacks
  - Some also refer to initialize vector as nonce
- Padding
  - final block may require a padding to fit a block size
  - Method
    - Add null Bytes
    - Add 0x80 and many 0x00
    - Add the *n* bytes with value *n*

# Electronic Codebook Book (ECB)

- Message is broken into independent blocks which are encrypted

- Each block is a value which is substituted, like a codebook, hence name

- Each block is encoded independently of the other blocks

$$C_i = E_K(P_i)$$

- Uses: secure transmission of single values

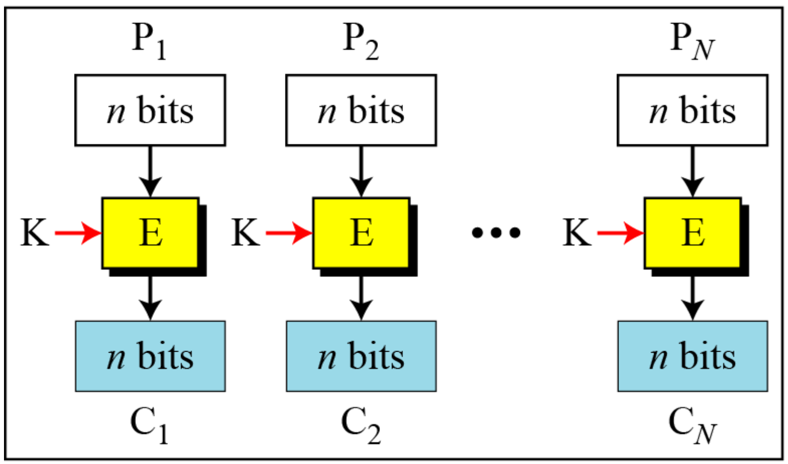
# Topics

- Overview of Modes of Operation
- **EBC, CBC, CFB, OFB, CTR**
- Notes and Remarks on each modes

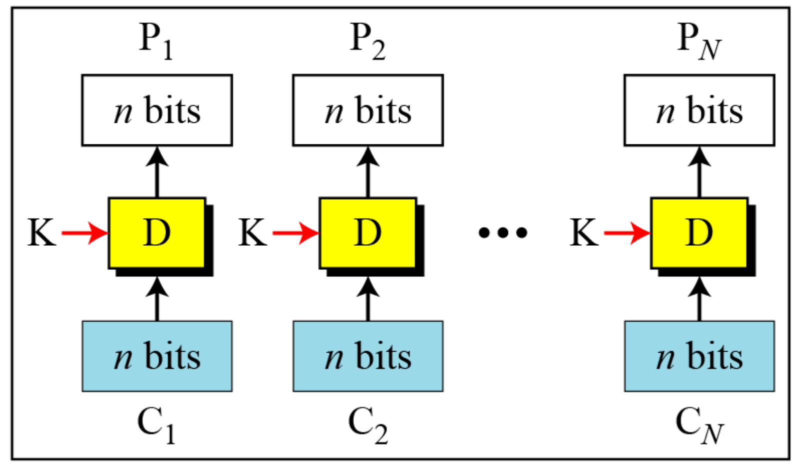
# ECB Scheme

Encryption: $C_i = E_K(P_i)$ Decryption: $P_i = D_K(C_i)$

E: Encryption D: Decryption
$P_i$: Plaintext block $i$ $C_i$: Ciphertext block $i$
K: Secret key



Encryption



Decryption

# Remarks on ECB

- Strength: it's simple.

- Weakness:
  - Repetitive information contained in the plaintext may show in the ciphertext, if aligned with blocks.
  - If the same message is encrypted (with the same key) and sent twice, their ciphertext are the same.

- Typical application:
  - secure transmission of short pieces of information (e.g. a temporary encryption key)

# Cipher Block Chaining (CBC)

- Solve security deficiencies in ECB
  - Repeated same plaintext block result different ciphertext block
- Each previous cipher blocks is chained to be input with current plaintext block, hence name
- Use Initial Vector (IV) to start process

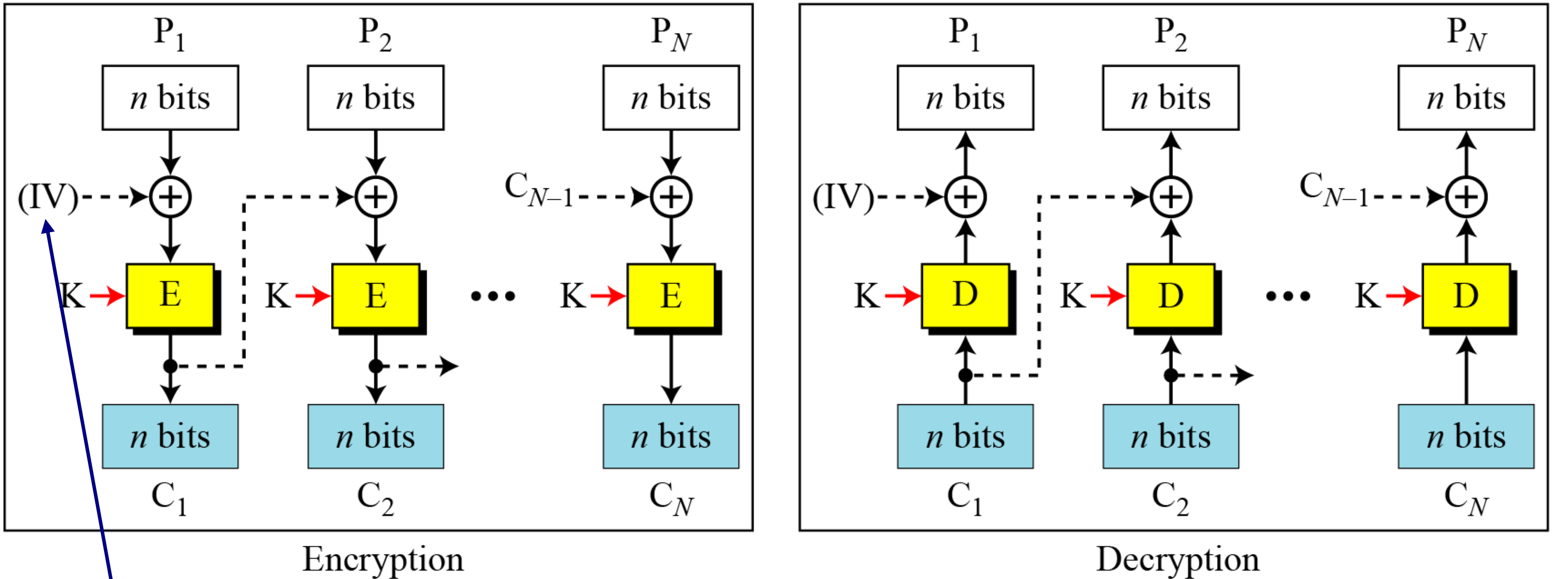
$$C_i = E_K (P_i \text{ XOR } C_{i-1})$$
$$C_0 = IV$$

- Uses: bulk data encryption, authentication

# CBC scheme

E: Encryption
$P_i$: Plaintext block $i$
K: Secret key

D : Decryption
$C_i$ : Ciphertext block $i$
IV: Initial vector ($C_0$)




**Encryption:**
$C_0 = IV$
$C_i = E_K (P_i \oplus C_{i-1})$

**Decryption:**
$C_0 = IV$
$P_i = D_K (C_i) \oplus C_{i-1}$

# Remarks on CBC

- The encryption of a block depends on the current and **all** blocks before it.
- So, repeated plaintext blocks are encrypted differently.
- Initialization Vector (IV)
  - May sent encrypted in ECB mode before the rest of ciphertext

# Cipher FeedBack (CFB)

- Use Initial Vector to start process
- 
- Encrypt previous ciphertext , then combined with the plaintext block using X-OR to produce the current ciphertext
- Cipher is fed back (hence name) to concatenate with the rest of IV
- Plaintext is treated as a stream of bits
  - Any number of bit (1, 8 or 64 or whatever) to be feed back (denoted CFB-1, CFB-8, CFB-64)
- Relation between plaintext and ciphertext

$$C_i = P_i \text{ XOR SelectLeft}(E_K(\text{ShiftLeft}(C_{i-1})))$$

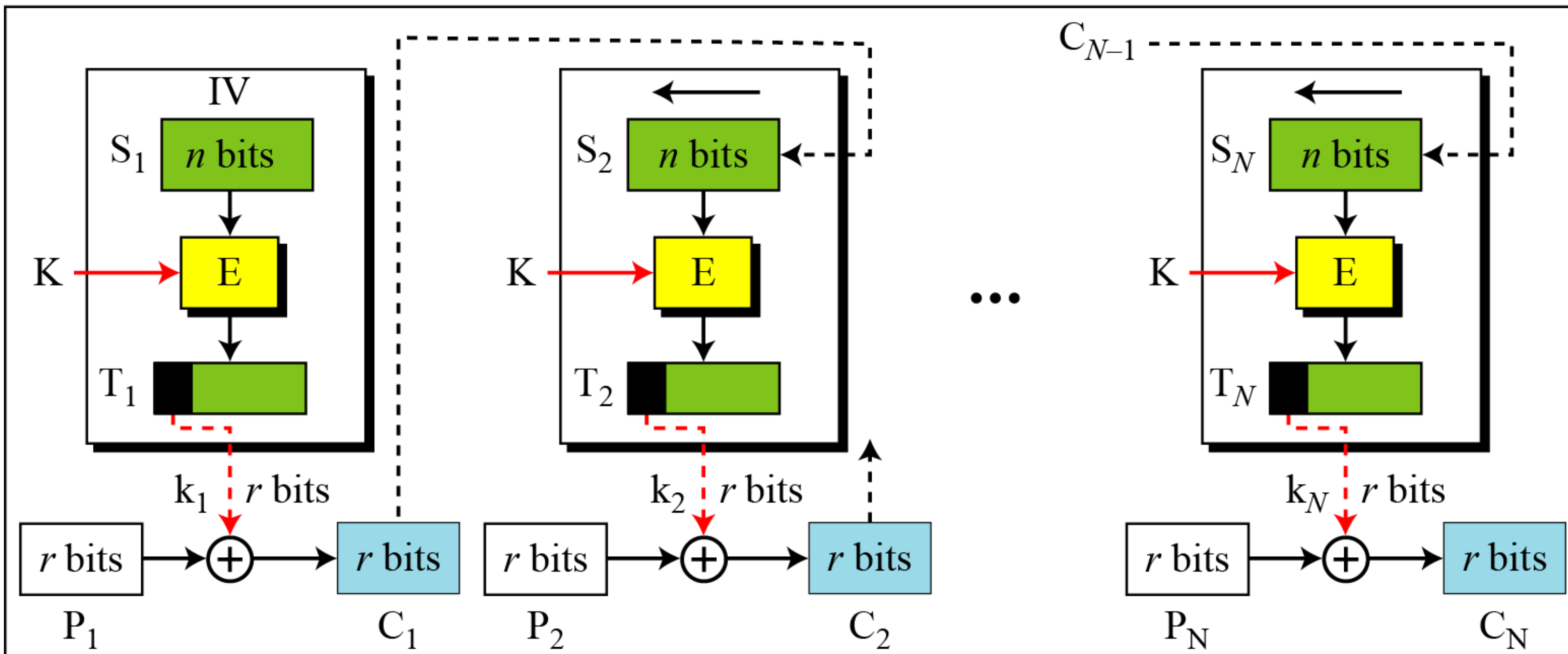
$$C_0 = IV$$

- Uses: stream data encryption, authentication

# CFB Scheme

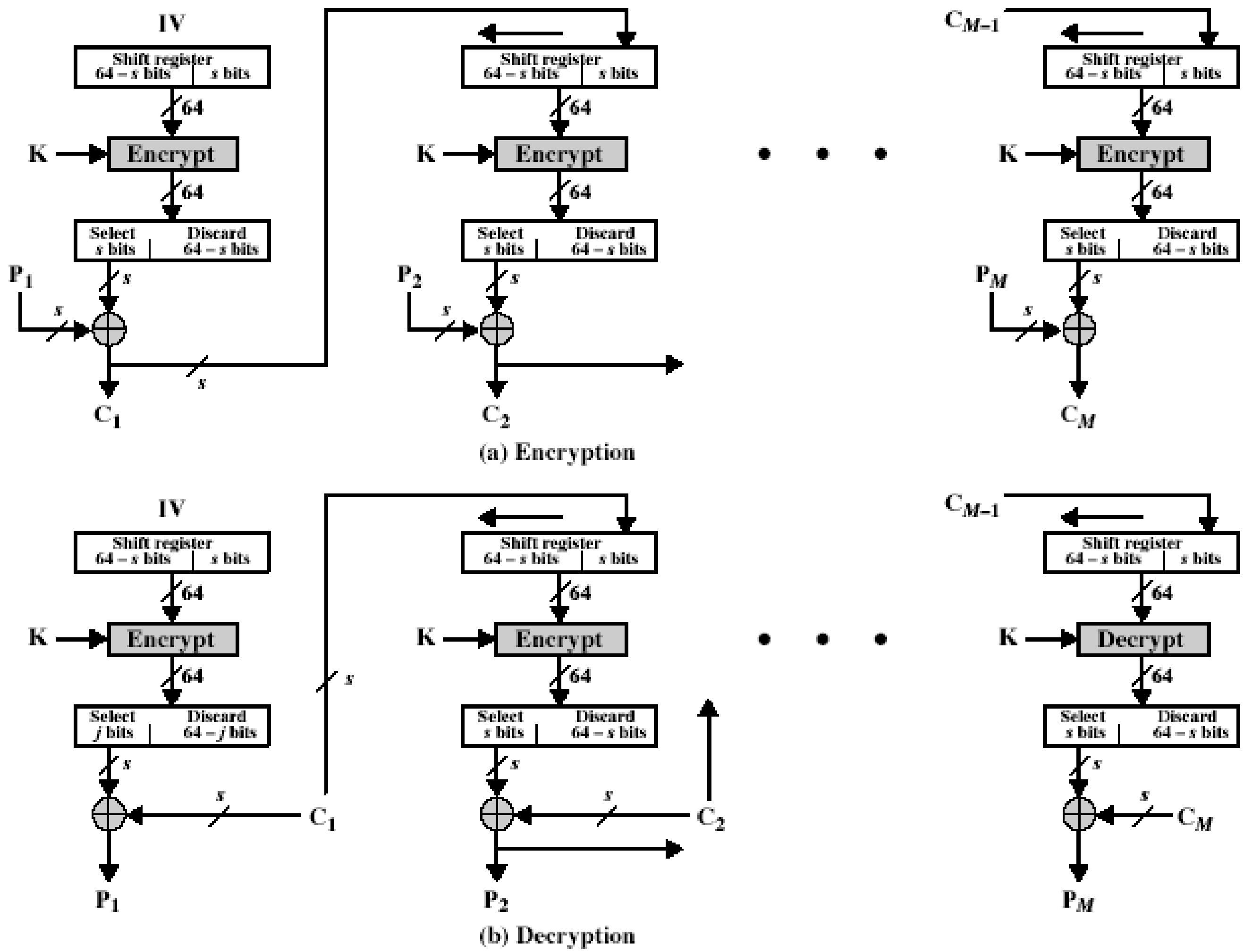
**Encryption:** $C_i = P_i \oplus \text{SelectLeft}_r\{E_K[\text{ShiftLeft}_r(S_{i-1}) \mid C_{i-1})]\}$
**Decryption:** $P_i = C_i \oplus \text{SelectLeft}_r\{E_K[\text{ShiftLeft}_r(S_{i-1}) \mid C_{i-1})]\}$

E : Encryption
$P_i$: Plaintext block *i*
K: Secret key
D : Decryption
$C_i$: Ciphertext block *i*
IV: Initial vector ($S_1$)
$S_i$: Shift register
$T_i$: Temporary register



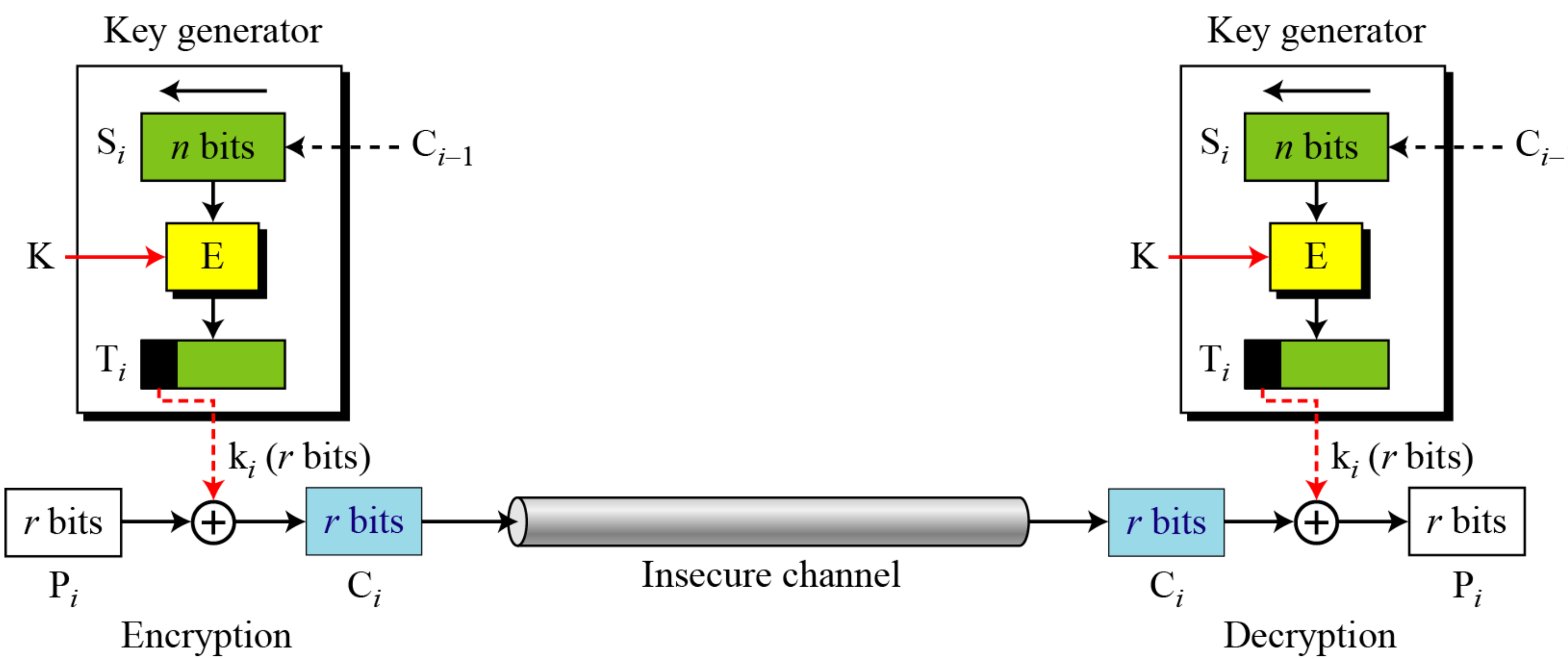
Encryption

# CFB Encryption/Decryption



# CFB as a Stream Cipher

- In CFB mode, encipherment and decipherment use the encryption function of the underlying block cipher.



# Remark on CFB

- The block cipher is used as a stream cipher.
  - enable to encrypt any number of bits e.g. single bits or single characters (bytes)
  - S=1 : bit stream cipher
  - S=8 : character stream cipher)
- A ciphertext segment depends on the current and all preceding plaintext segments.
- A corrupted ciphertext segment during transmission will affect the current and next several plaintext segments.

# Output FeedBack (OFB)

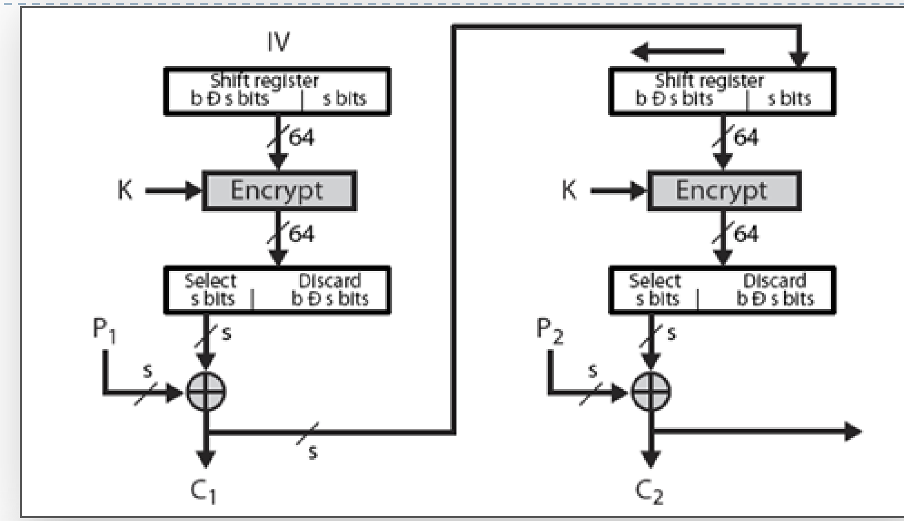
- Very similar to CFB
- But output of the encryption function output of cipher is fed back (hence name), instead of ciphertext
- Feedback is independent of message
- Relation between plaintext and ciphertext

$$C_i = P_i \text{ XOR } O_i$$
$$O_i = E_K(O_{i-1})$$
$$O_0 = IV$$

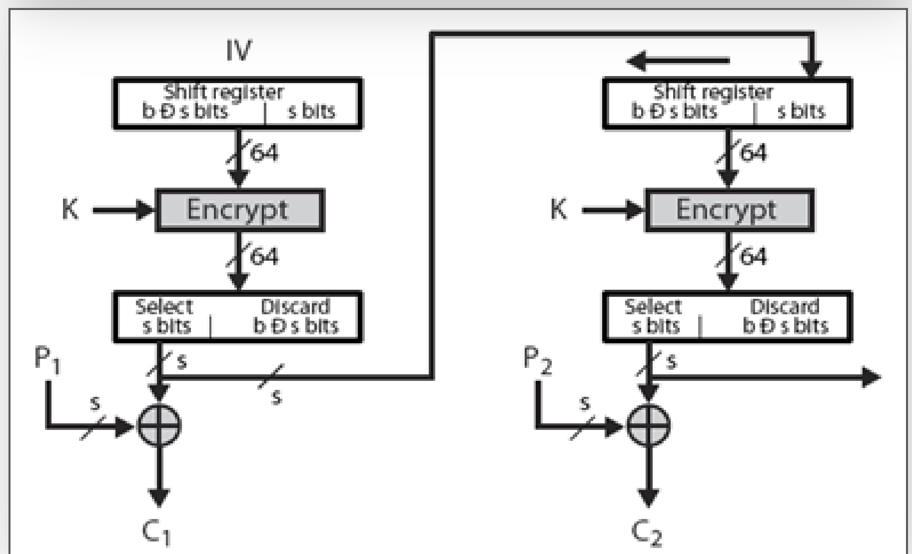
- Uses: stream encryption over noisy channels

# CFB V.S. OFB

Cipher Feedback

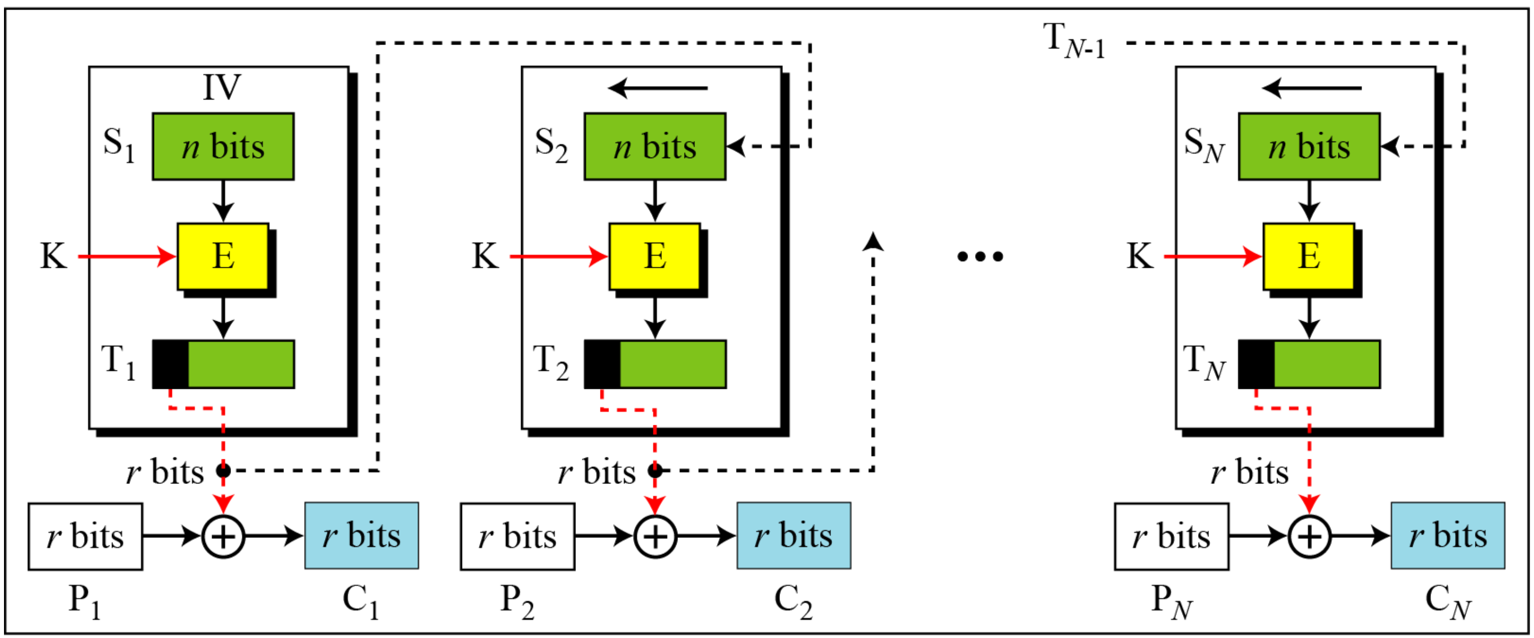



Output Feedback



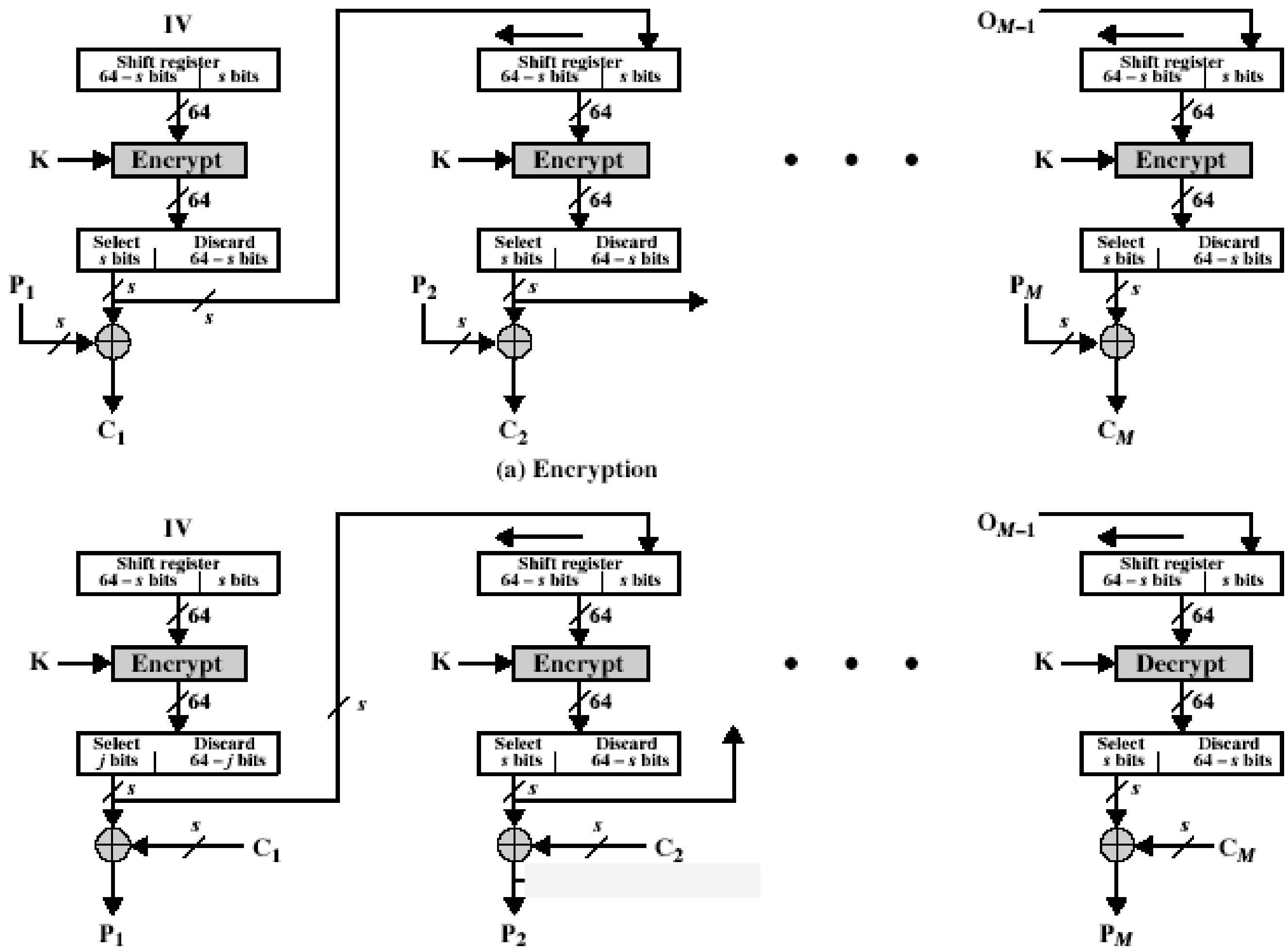
# OFB Scheme

E : Encryption
D : Decryption
$S_i$: Shift register
$P_i$: Plaintext block i
$C_i$ : Ciphertext block i
$T_i$: Temporary register
K: Secret key
IV: Initial vector ($S_1$)




Encryption

# OFB Encryption and Decryption

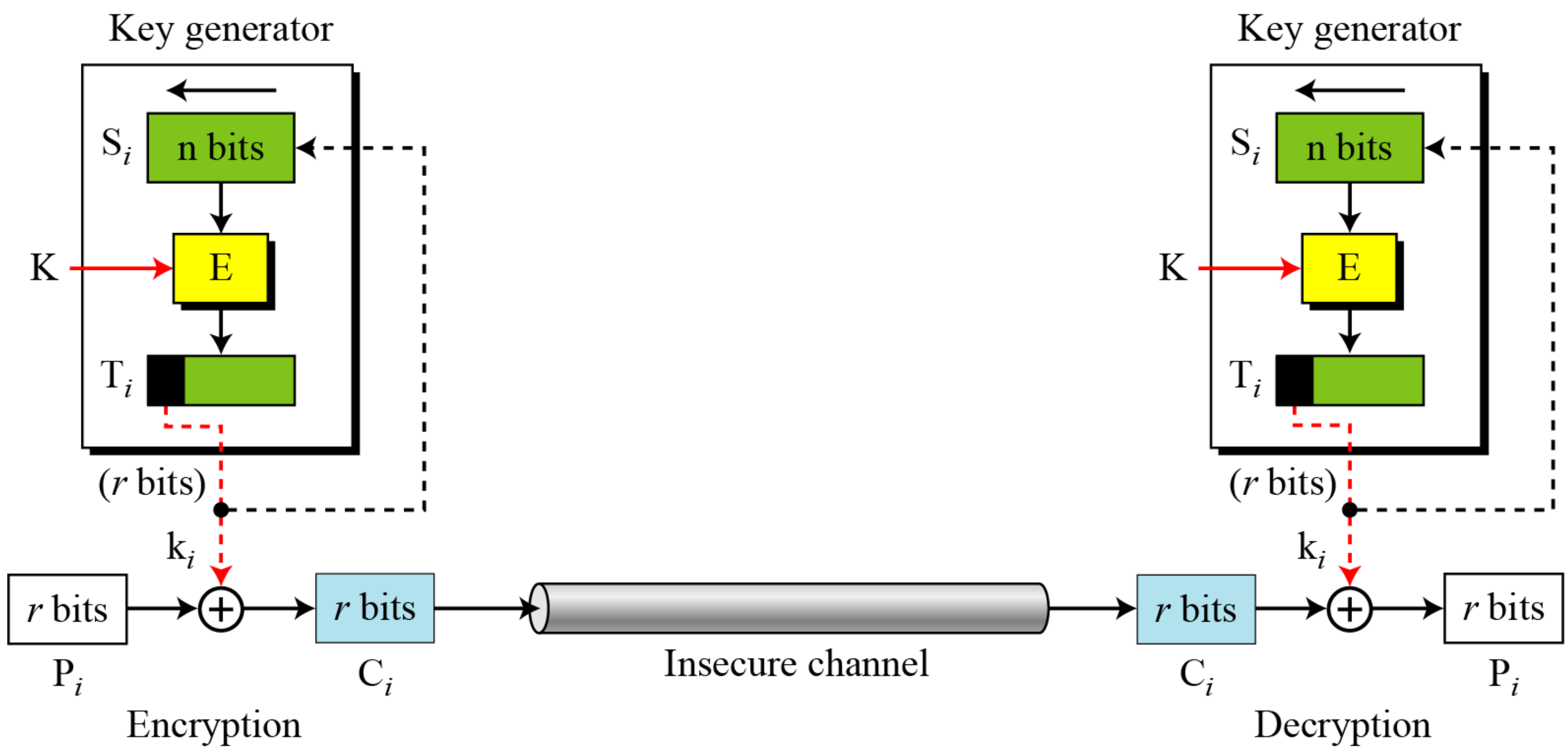



(a) Encryption

(b) Decryption

# OFB as a Stream Cipher

- In OFB mode, encipherment and decipherment use the encryption function of the underlying block cipher.



# Remarks on OFB

- Each bit in the ciphertext is independent of the previous bit or bits. This avoids error propagation
- Pre-compute of forward cipher is possible
- Security issue
  - when $j^{th}$ plaintext is known, the $j^{th}$ output of the forward cipher function will be known
  - Easily cover $j^{th}$ plaintext block of other message with the same IV
- Require that the IV is a nonce

# Counter (CTR)

- Encrypts counter value with the key rather than any feedback value (no feedback)
- Counter for each plaintext will be different
  - can be any function which produces a sequence which is guaranteed not to repeat for a long time
- Relation

$$C_i = P_i \text{ XOR } O_i$$

$$O_i = E_K(i)$$

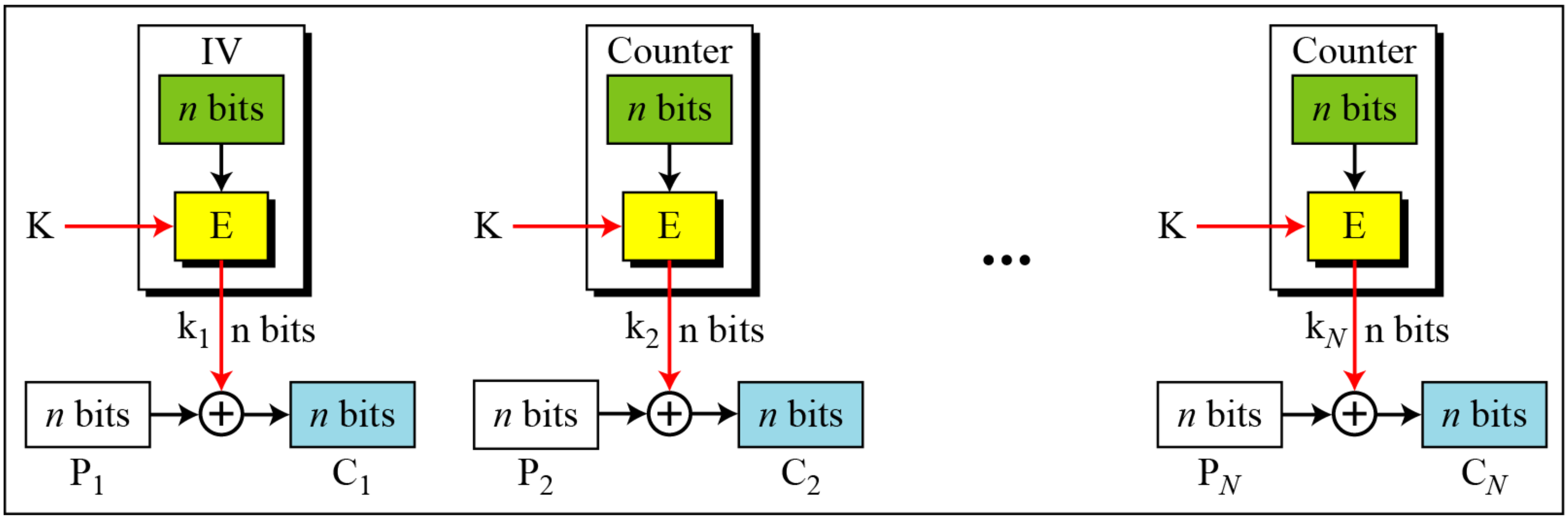
- Uses: high-speed network encryptions

# CTR Scheme

E : Encryption
$P_i$ : Plaintext block *i*
K : Secret key

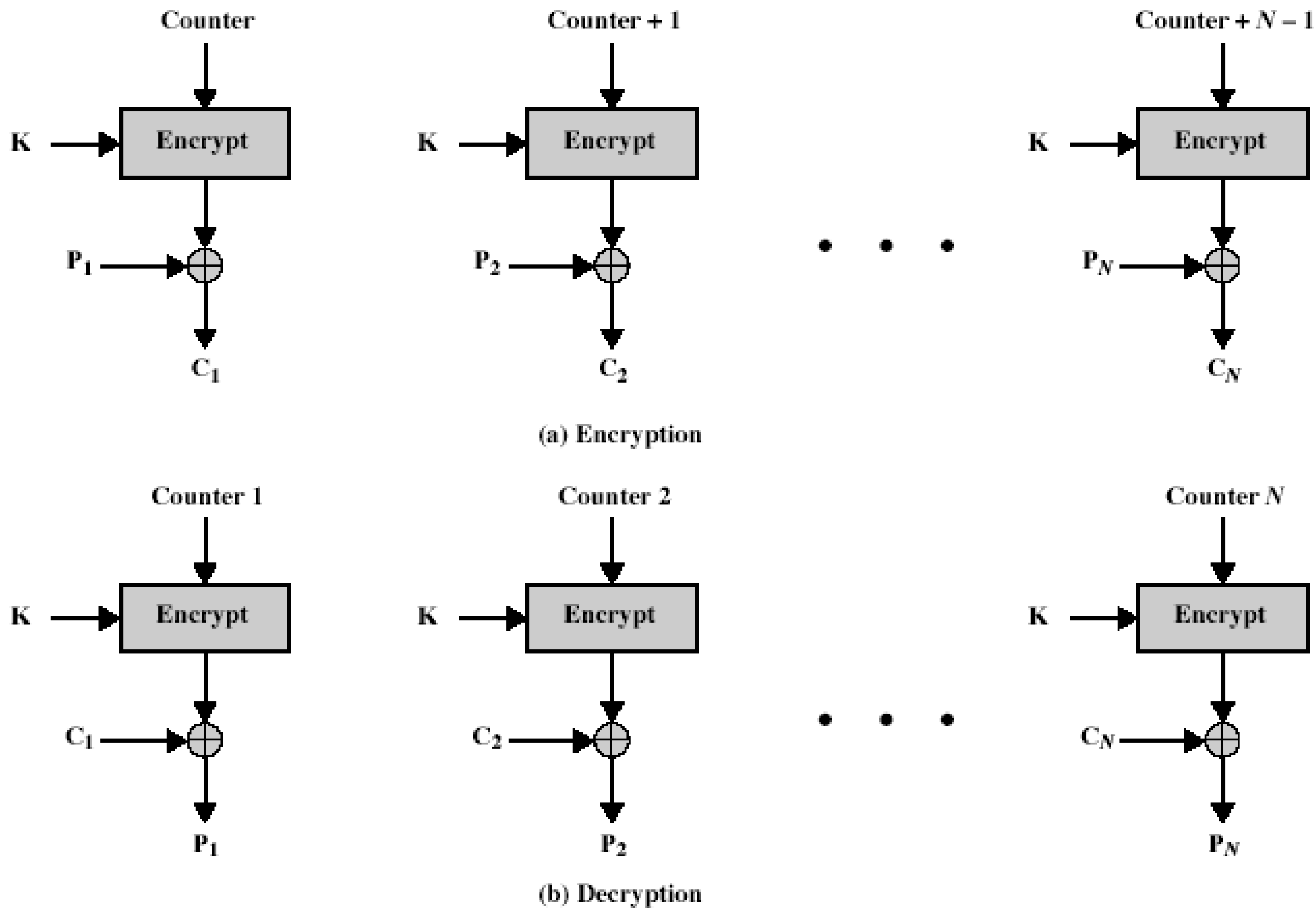
IV: Initialization vector
$C_i$ : Ciphertext block *i*
$k_i$ : Encryption key *i*

The counter is incremented for each block.

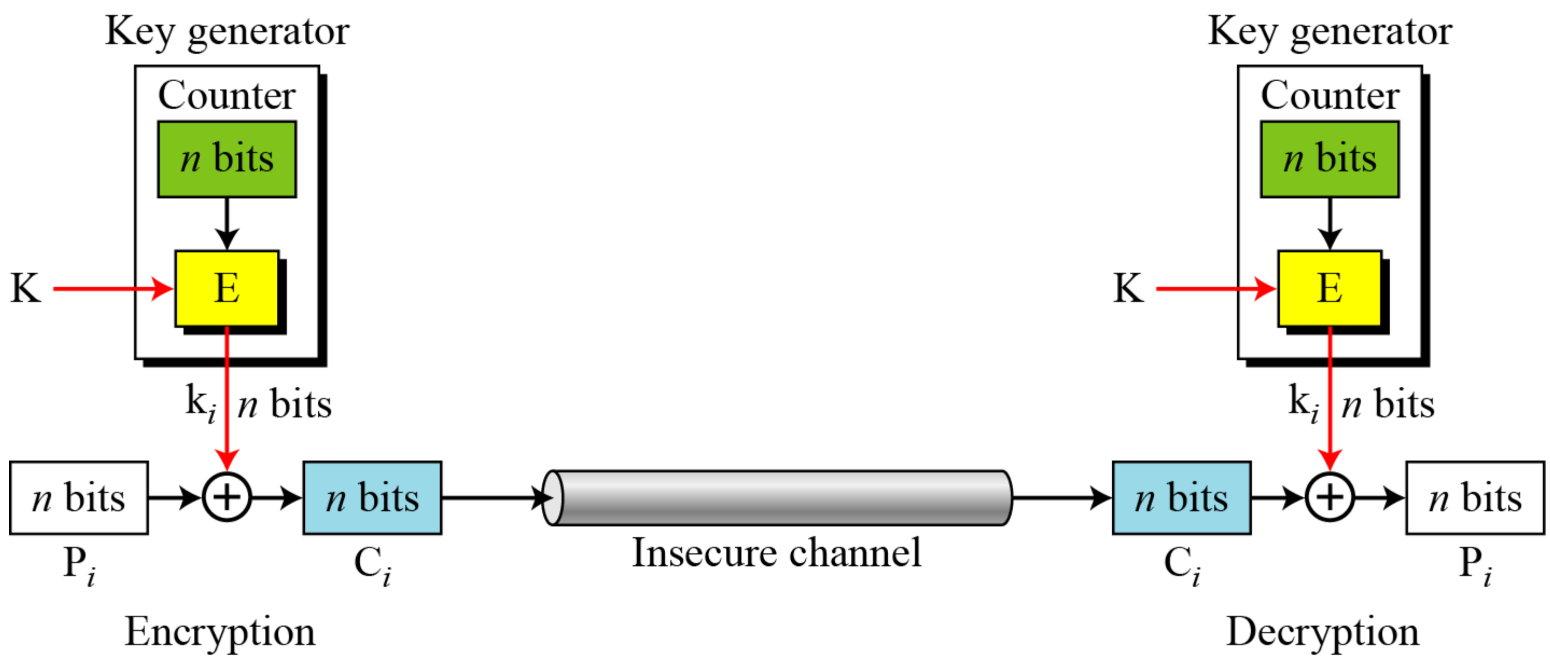



Encryption

# CTR Encryption and Decryption



# OFB as a Stream Cipher



# Remark on CTR

- Strengthes:
  - Needs only the encryption algorithm
  - Random access to encrypted data blocks
    - blocks can be processed (encrypted or decrypted) in parallel
  - Simple; fast encryption/decryption

- Counter must be
  - Must be unknown and unpredictable
  - pseudo-randomness in the key stream is a goal

# Topics

- Overview of Modes of Operation
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- **Notes and Remarks on each modes**

# Remark on each mode

- Basically two types:
  - block cipher
  - stream cipher

- CBC is an excellent block cipher

- CFB, OFB, and CTR are stream ciphers

- CTR is faster because simpler and it allows parallel processing

# Modes and IV

- An IV has different security requirements than a key
- Generally, an IV will not be reused under the same key
- CBC and CFB
  - reusing an IV leaks some information about the first block of plaintext, and about any common prefix shared by the two messages
- OFB and CTR
  - reusing an IV completely destroys security

# CBC and CTR comparison

| CBC | CTR |
|---|---|
| Padding needed | No padding |
| No parallel processing | Parallel processing |
| Separate encryption and decryption functions | Encryption function alone is enough |
| Random IV or a nonce | Unique nonce |
| Nonce reuse leaks some information about initial plaintext block | Nonce reuse will leak information about the entire message |

# Comparison of Different Modes

| *Operation Mode* | *Description* | *Type of Result* | *Data Unit Size* |
|---|---|---|---|
| ECB | Each $n$-bit block is encrypted independently with the same cipher key. | Block cipher | $n$ |
| CBC | Same as ECB, but each block is first exclusive-ored with the previous ciphertext. | Block cipher | $n$ |
| CFB | Each $r$-bit block is exclusive-ored with an $r$-bit key, which is part of previous cipher text | Stream cipher | $r \leq n$ |
| OFB | Same as CFB, but the shift register is updated by the previous $r$-bit key. | Stream cipher | $r \leq n$ |
| CTR | Same as OFB, but a counter is used instead of a shift register. | Stream cipher | $n$ |

# Comparison of Modes

| Mode | Description | Application |
|---|---|---|
| ECB | 64-bit plaintext block encoded separately | Secure transmission of encryption key |
| CBC | 64-bit plaintext blocks are XORed with preceding 64-bit ciphertext | Commonly used method. Used for authentication |
| CFB | s bits are processed at a time and used similar to CBC | Primary stream cipher. Used for authentication |

# Comparison of Modes

| Mode | Description | Application |
|---|---|---|
| OFB | Similar to CFB except that the output is fed back | Stream cipher well suited for transmission over noisy channels |
| CTR | Key calculated using the nonce and the counter value. Counter is incremented for each block | General purpose block oriented transmission.<br>Used for high-speed communications |

# Final Notes

- ECB, CBC, OFB, CFB, CTR, and XTS modes only provide confidentiality
- To ensure an encrypted message is not accidentally modified or maliciously tampered requires a separate Message Authentication Code (MAC)
- Several MAC schemes
  - HMAC, CMAC and GMAC
- But.. compositing a confidentiality mode with an authenticity mode could be difficult and error prone
- New modes combined confidentiality and data integrity into a single cryptographic primitive
  - CCM, GCM, CWC, EAX, IAPM and OCB

Q&A